EFFECTS OF THE 1960 CHILEAN EARTHQUAKE TSUNAMI IN NORTH AMERICA

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Abstract: The role played by the 1960 Chilean earthquake tsunami in generating the interest for modern research on tsunamis is briefly reviewed. The effects of this tsunami in North America, particularly in the USA and Canada are discussed. The tsunami had very significant amplitudes on the various islands of Hawaii, but less than 2 m in amplitude elsewhere in the USA as well as in Canada. Numerical model simulation of this tsunami effects on the Pacific Coast of Canada confirms the above results.

1.0 INTRODUCTION

The 1960 Chilean earthquake tsunami was one of the major events that triggered modern tsunami research. Some of the key milestones are identified here, at least from a North American point of view. Starting in the late 19th century, there was active tsunami research in Japan. The Aleutian earthquake tsunami of April l, 1946 generated the first serious interest in the U.S. in tsunami prediction and a tsunami warning system was developed by the Coast and Geodetic Survey. Subsequently, the Pacific Tsunami Warning Center (PTWC) was established in Ewa Beach, on Oahu Island in Hawaii.

The 1960 Chilean earthquake tsunami with Pacific wide damage triggered great interest in modern tsunami research, making use of the newly emerging technology of computer models. Four years later, the Alaska earthquake tsunami of March 1964 created further interest. The Inter-Governmental Oceanographic Commission (IOC) of UNESCO established in collaboration with several Pacific countries, the International Tsunami Warning System in the Pacific (ITSU) and in collaboration with the National Oceanic and Atmospheric Administration (NOAA) of USA, started the International Tsunami Information Center (ITIC) in Honolulu. The International Union of Geodesy and Geophysics (IUGG) established in 1959 and international Tsunami Commission. The U.S. also set up the Alaska Tsunami Warning Center (ATWC) at Palmer, Alaska.

2.0 The 1960 Chilean Earthquake Tsunami

The general tectonic features of Chile are shown in Figure 1. Figure 2 shows the epicenter and the area of the coast lines of Chile and Peru affected by this tsunami. The various regions around the Pacific Basin influenced to varying degrees by this tsunami are shown in Figure 3.

The effects of the 1960 Chilean earthquake tsunami were felt all around the Pacific Basin, to varying degree. The earthquake had a Richter magnitude of 8.6 (Lander and

Lockridge, 1989) and the earthquake and tsunami together killed over a thousand people in Chile and caused damage in excess of 500 Million U.S. Dollars (at the 1960 levels). Locally tsunami amplitudes up to 25 m have been reported, and as far away as Japan, the waves were 6 m high, and caused great destruction and some loss of life.

Here we will concentrate on the tsunami effects in North America, in particular, USA and Canada.

3.0 1960 Chilean Tsunami Effects in USA

In USA, Hawaii experienced the maximum effects from this tsunami. Figure 4 shows various tsunamis from Chile, including the one in May 1960 that caused destruction in the Hawaiian Islands.

Figures 5, 6, 7 and 8 respectively show the amplitudes of the tsunami at various locations on the islands of Hawaii, Maui, Kauai and Oahu.

In Hilo, Hawaii, sixty-one people were killed and forty-three were seriously injured. The third wave transformed itself into a bore and caused significant land inundation up to the 6 m contour in Hilo Bay. Damage also occurred at Kahului on the north coast of Maui. Some damage took place on the islands of Molokai and Lanai with only minor damage on the islands of Oahu and Kauai. The following maximum tsunami amplitudes were reported: 10.7 m at Hilo on the big island of Hawaii, 5.2 m at Kahului (Maui), 4.5 m on the west coast of Oahu, and 4.3 at Hanapepe and Haena, respectively on the south and north coasts of Kauai. The Chilean tsunami also affected Alaska as well as the west coasts of USA and Canada. At Massacre Bay, Alaska, the maximum tsunami amplitude was 1.7 m. At Crescent City, California, the maximum amplitude was also 1.7 m. Major damage occurred in Los Angeles and Long Beach Harbours. Horizontal currents created by the tsunami were about 22 khp. At Terminal Island, the Coast Guard landing including the tide gauge was washed 5.6 km to sea. Damage also took place in San Diego, Santa Monica, and Santa Barbara.

4.0 1960 Chilean Tsunami Effects in Canada

In Canada, the tsunami penetrated northward and eastward through very complex coastal inlet systems of the Province of British Columbia. Whereas forerunners to this tsunami were reported as far away as Japan, none were noticed in Canada. The tsunami took just over 17 hours to reach Canada with amplitudes of up to 1.3 m at Tofino and possibly up to 2.1 m at Shields Bay. Our numerical simulations of this tsunami gave maximum amplitudes of 1.2 m near Quakinsh on the northern part of Vancouver Island.

Figure 9 shows the southern part of the Coast of British Columbia. Figure 10 shows some of the complex inlet systems of British Columbia.

S.O. Wigen (unpublished data) described the tsunami on the west coast of Canada generated by the Chilean earthquake of May 22, 1960. The tsunami arrived on the B.C. coast at 0421 (Pacific Standard time) on May 23, thus the travel time was over 17 h. The maximum amplitude of the tsunami at Tofino was 1.3 m, whereas at Shields Bay it could have been 2.1 m Loucks (1962) studied this tsunami on the Canadian coast by spectrum analysis of observed records.

Loucks (1962) applied the concept of interaction of waves and currents developed by Longuet-Higgins and Stewart (1961, 1962, 1964) to explain the propagation of this tsunami to Johnson Point through Slingsby Channel on the west coast of Canada. A very interesting observation during the 1960 Chilean earthquake tsunami was that that tsunami propagated through the narrows, channels, and rapids to arrive at Johnson Point, and still retained an appreciable amplitude. The concept Loucks invoked to explain this was that the waves could extract energy from an opposing current and lose energy to a following current via Reynolds stresses. In the approaches to Johnson Point, the Reynolds stresses would be acting to increase the energy of the wave. Loucks stated that without the Reynolds stress effect, the wave would have arrived at Johnson Point with greater dissipation.

5.0 TSUNAMI FORERUNNERS

Nakamura and Watanabe (1961) defined the tsunami forerunner as a series of oscillations of the water level preceding the arrival of the main tsunami waves (Figure 11). The forerunner, when it exists, has typically smaller amplitudes and periods than those of the main tsunami and could be easily distinguished. They stated that there has been no clear indication of tsunami forerunners on either the North or South American coasts.

Nakamura and Watanabe explained that absence of the forerunner on the coasts of North and South America was because of the oblique nature of the incidence of the initial wave on the costs. They explained that the existence of the forerunner at the other places (Japan, for example) was due to the resonance in bays and shelves that could occur before the arrival of the main tsunami.

If this is the correct explanation for the existence of the forerunner, then one can ask why the forerunner does not exist on the coasts of North and South America, as resonance indeed occurs there (Murty, 1977). This is still and unanswered question.

Nakamura and Watanabe (1961) studied the forerunners of the Chilean tsunami of May 1960. They remarked that no previous tsunamis on the Japanese coast showed forerunners and that the Chilean tsunami did not cause forerunners at any place other than Japan.

Figure 11 shows the forerunner at Hanasaki for the May 1960 Chilean earthquake tsunami. Figure 12 shows that no forerunners were recorded on the Pacific Coast of

Canada for either the Chilean earthquake tsunami of May 1960 or the Alaska earthquake tsunami of March 1964.

6.0 NUMERICAL MODEL

A three part numerical model was developed (Dunbar et al, 1989 a, b) for simulating the tsunami amplitudes on the Pacific coast of Canada from four different earthquakes. For the present discussion, our interest is in 2, the 1960 Chilean earthquake. Figure 13 shows the region modeled by the Deep Ocean Model (DOM) for tsunami generation and propagation. The model grid was 0.5 x 0.5 degree in both latitude and longitude and the model was done in the framework of spherical polar coordinates.

Figure 14 shows the bottom motion due to the earthquake, which was used as input data into the numerical model. Figure 15 shows the two shelf models with a grid resolution of 5 km in rectangular Cartesian coordinates. Figure 16 and 17 respectively show the inlet systems of the northern and southern parts of British Columbia, which were modeled as one-dimensional systems with a grid resolution of 2 km. Table 1 lists these inlet systems.

Table 1
British Columbia Inlet Systems Included in Tsunami Simulations
(From Dunbar et al, 1989a)

System	Areas Included
A	Portland Canal Observatory Inlet-Hastings Arm Alice Arm Khutzeymateen Inlet Work Channel
B	Prince Rupert Inlet
C	Rennell Sound
D	Tasu Sound
E	Douglas Channel Kildala Arm Gardner Canal

	Sheep Passage – Mussel Inlet
F	Spiller Channel Roscoe Inlet Cousins Inlet Cascade Inlet Dean Channel Kwatna Inlet South Bentinck Arm
G	Laredo Inlet
H	Surf Inlet
I	Rivers Inlet Moses Inlet
J	Smith Inlet
K	Mereworth Sound Belize Inlet Nugent Sound Seymour Inlet
L	Holberg-Rupert Inlet Quatsino Sound – Neroutsos Inelet Forward Inlet
M	Klaskino Inlet
N	Quoukinsh Inlet
O	Nuchalitz Inlet
P	Port Eliza Espinosa Inlet Tahsis Inlet Cook Channel –Tiupana Inlet Zuciarte Channel – Muchalat Inlet
Q	Sydney Inlet Shelter Inlet Herbert Inlet
R	Pipestem Inlet
S	Effingham Inlet
T	Alberni Inlet

Figure 18 shows some of the inlets in detail. According to Table 2, the maximum tsunami amplitude for this event occurred at location 119 on then northern part of the Vancouver Island.

Table 2

Maximum Tsunami Water Levels and Currents for System M, N, O, and P

(From Dunbar et al, 1989b)

		Source Region					Source Region				
Location Number	Inlet System	1a	1b	2	3	4	1a	1b	2b	3	4
		Water Level (m)					Current Speed (m/s)				
117	M	3.0	3.7	0.4	5.5	2.3	2.08	2.40	0.45	2.99	2.32
118	M	4.2	5.0	0.7	5.7	3.7	0.37	0.43	0.09	0.97	0.50
119	N	8.6	10.1	1.2	13.0	4.6	0.80	0.98	0.13	2.29	1.04
120	N	1.3	1.6	0.3	3.9	1.7	-	-	-	-	-
121	O	2.1	2.6	0.3	3.3	1.2	0.76	0.91	0.17	1.93	0.98
122	O	3.3	3.8	0.6	4.4	1.7	0.56	0.62	0.12	1.22	0.40
123	O	0.2	0.2	0.0	0.2	0.1	0.02	0.03	0.01	0.04	0.02
124	O	0.2	0.2	0.0	0.2	0.1	0.00	0.00	0.00	0.00	0.00
125	O	1.9	2.4	0.3	2.9	1.1	-	-	-	-	-
126	P	1.7	2.1	0.2	2.9	2.3	0.74	0.91	0.06	1.76	1.06
127	P	2.4	3.0	0.2	4.5	1.8	1.33	1.64	0.13	2.66	0.47
128	P	5.9	7.3	0.4	10.6	1.6	0.33	0.40	0.04	0.86	0.181
129	P	6.1	7.5	0.4	10.8	1.7	0.13	0.16	0.02	0.36	0.09
130	P	6.5	8.0	0.4	11.1	2.2	0.22	0.26	0.03	0.68	0.24

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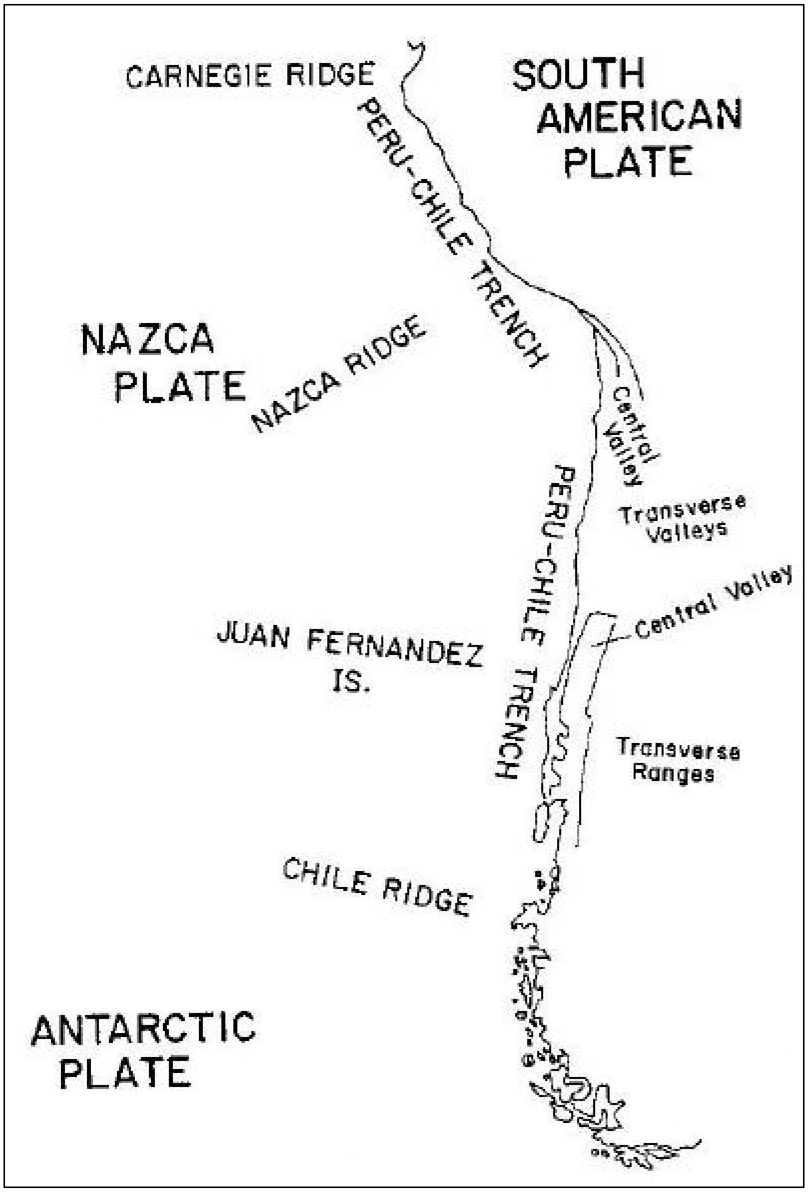

Figure 1

Geologic Features of Peru-Chile

(From Lockridge, 1985)

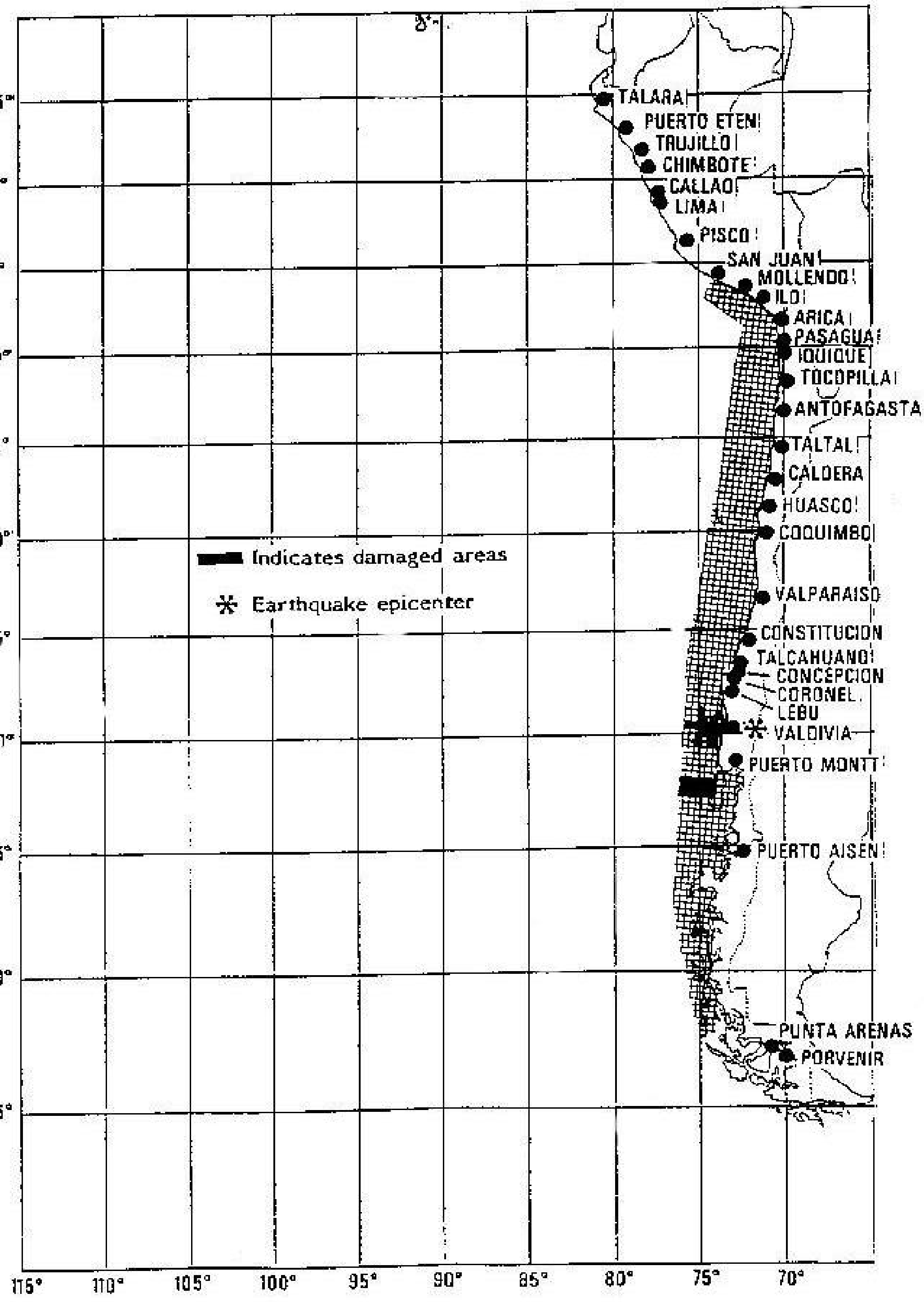

Figure 2

Area of Peru-Chile Coastline Affected by Chile Tsunami of May 22, 1960

(From Lockridge, 1985)

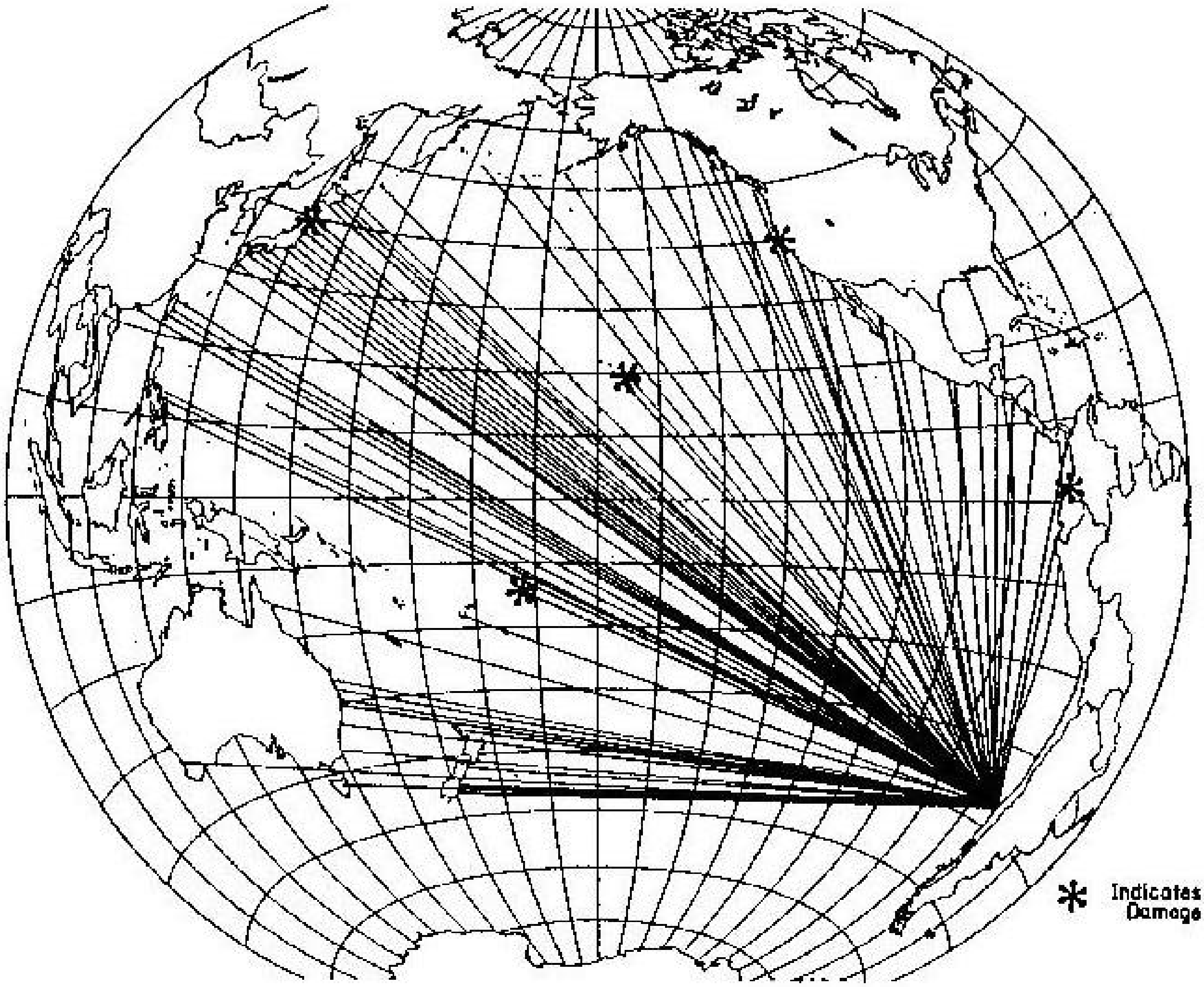

Figure 3

Areas Outside Peru-Chile Reporting Chile Tsunami of May 22, 1960

(From Lockridge, 1985)

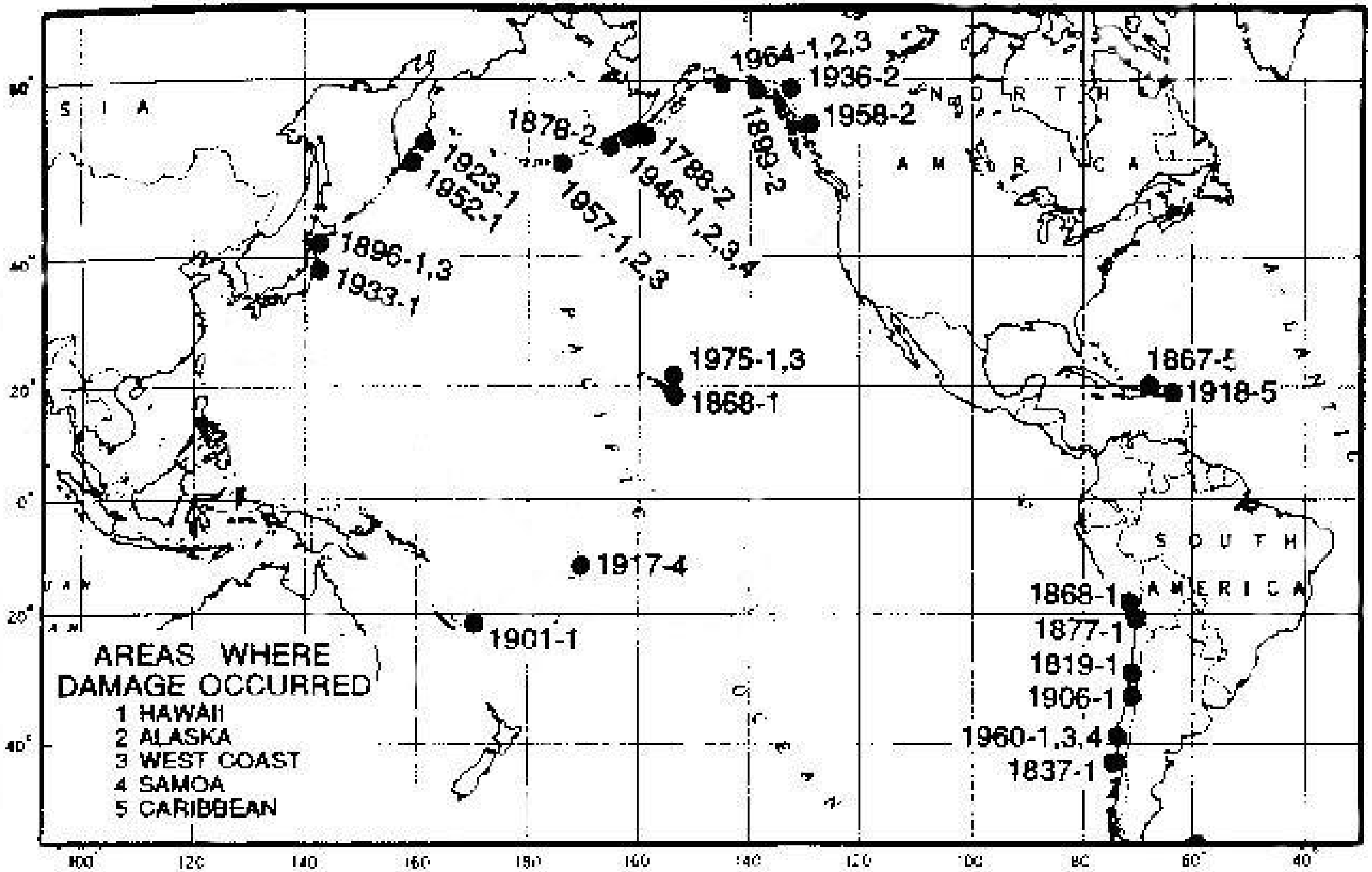

Figure 4

Epicenters of earthquakes that generated destructive tsunamis in the United States and Possessions

(From Lander and Lockridge,1989)

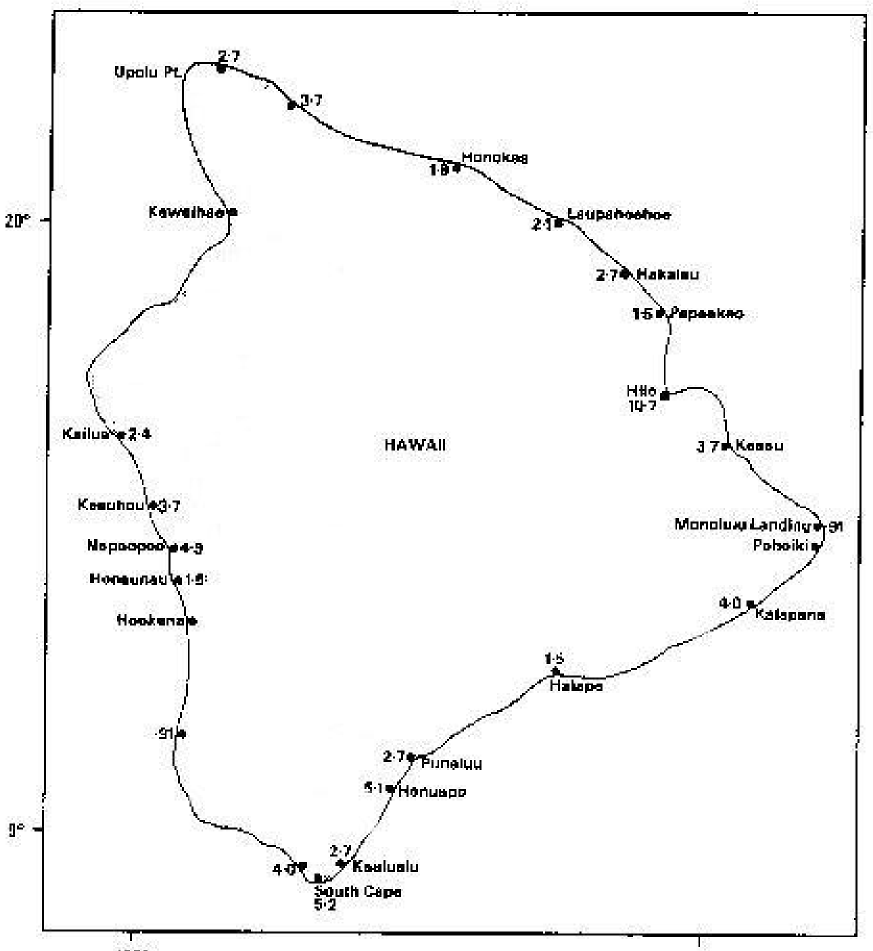

Figure 5

Hawaii, showing run-up heights (m) above mean lower low water during 1960 tsunami

(Cox and Mink 1963)

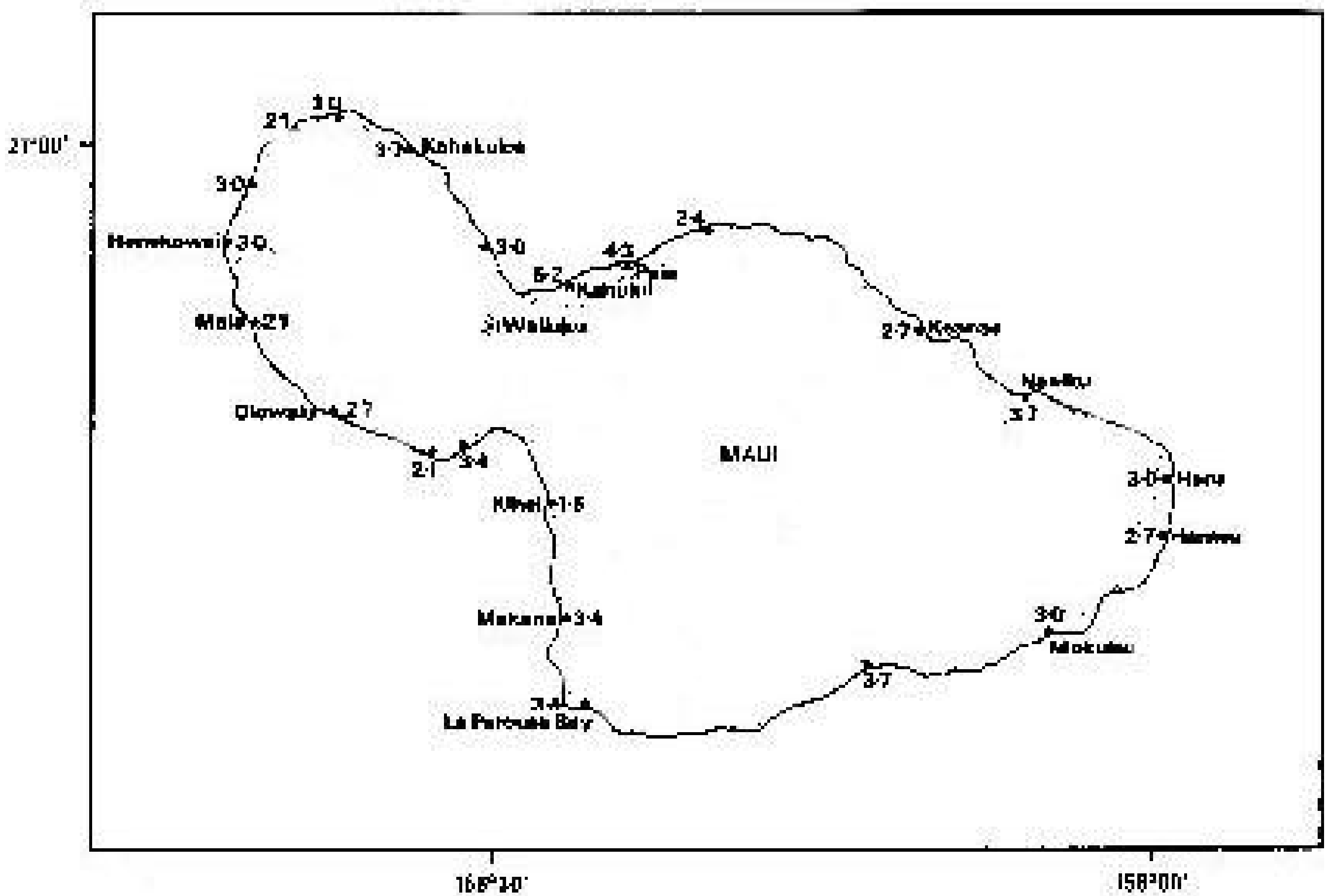

Figure 6

Maui showing run-up heights (m) above mean lower low water during 1960 tsunami

(Cox and Mink 1963)

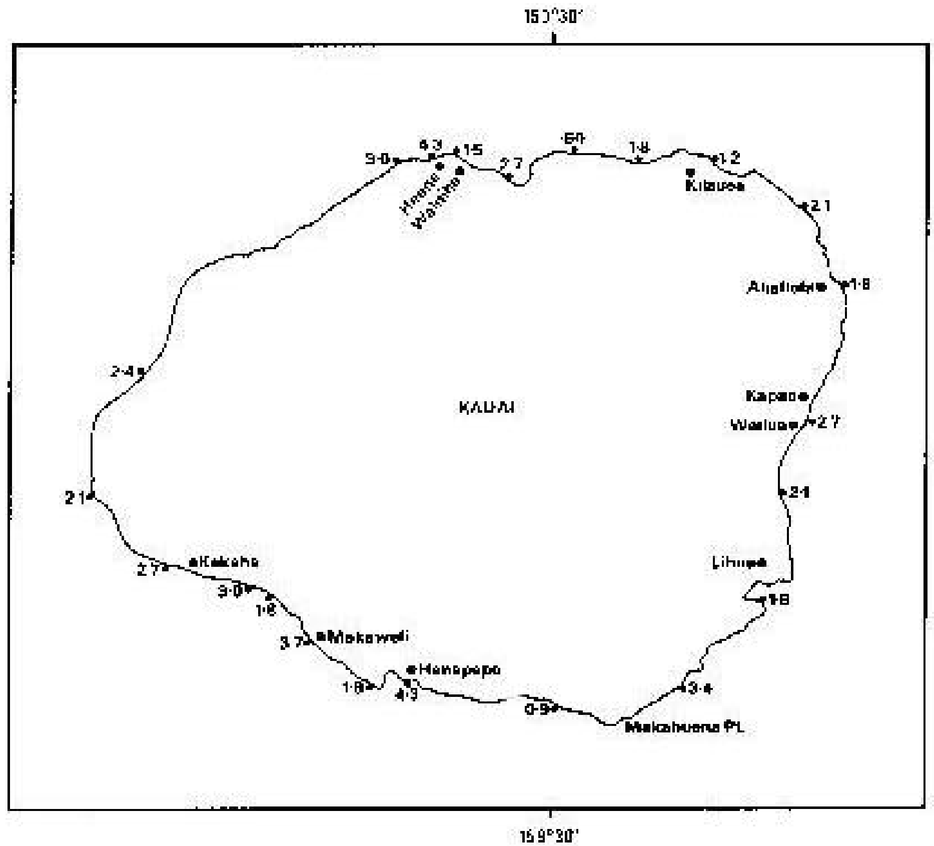

Figure 7

Kauai, showing run-up heights (m) above mean lower low water during 1960 tsunami

(Cox and Mink 1963)

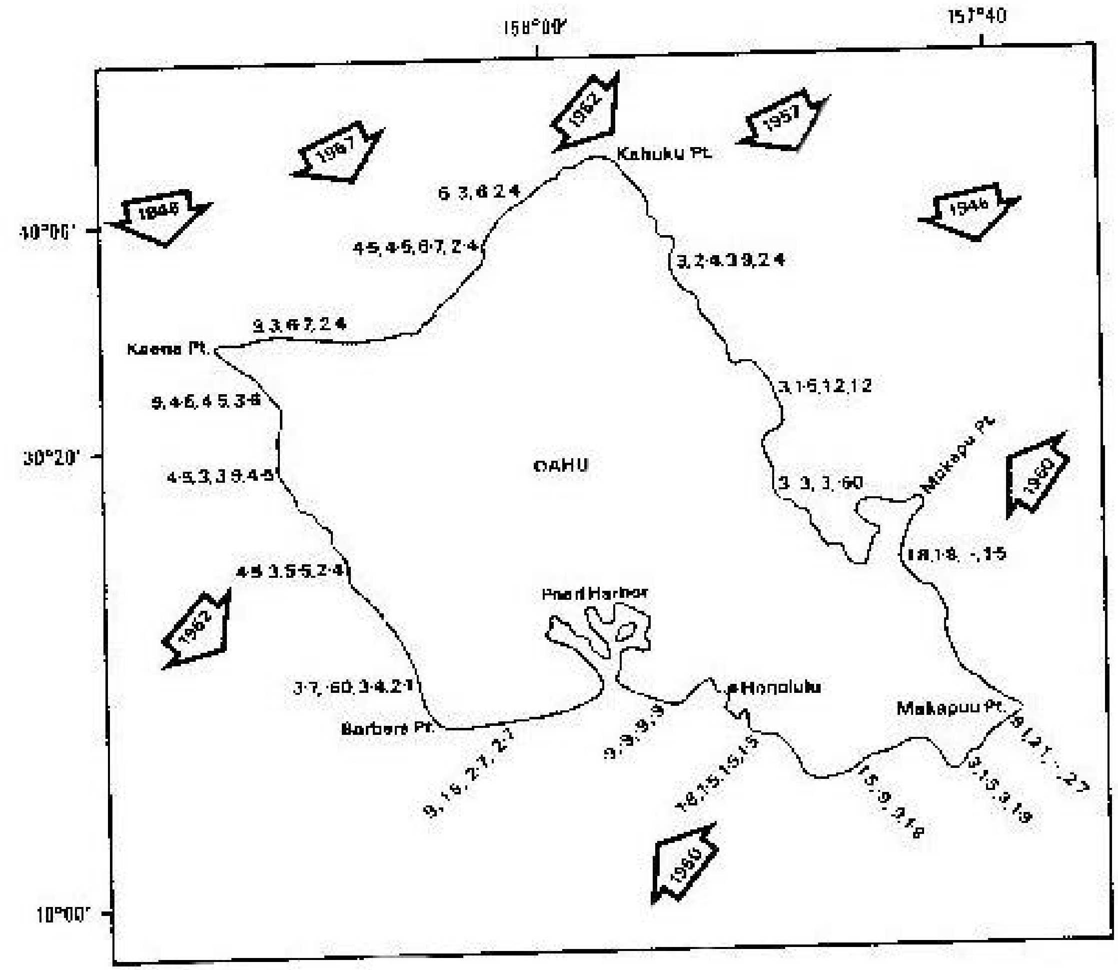

Figure 8

Oahu, showing run-up heights (m) and directions of approach of 1946, 1952, 1957 and 1960 tsunami - direction of travel (Cox and Mink 1963)

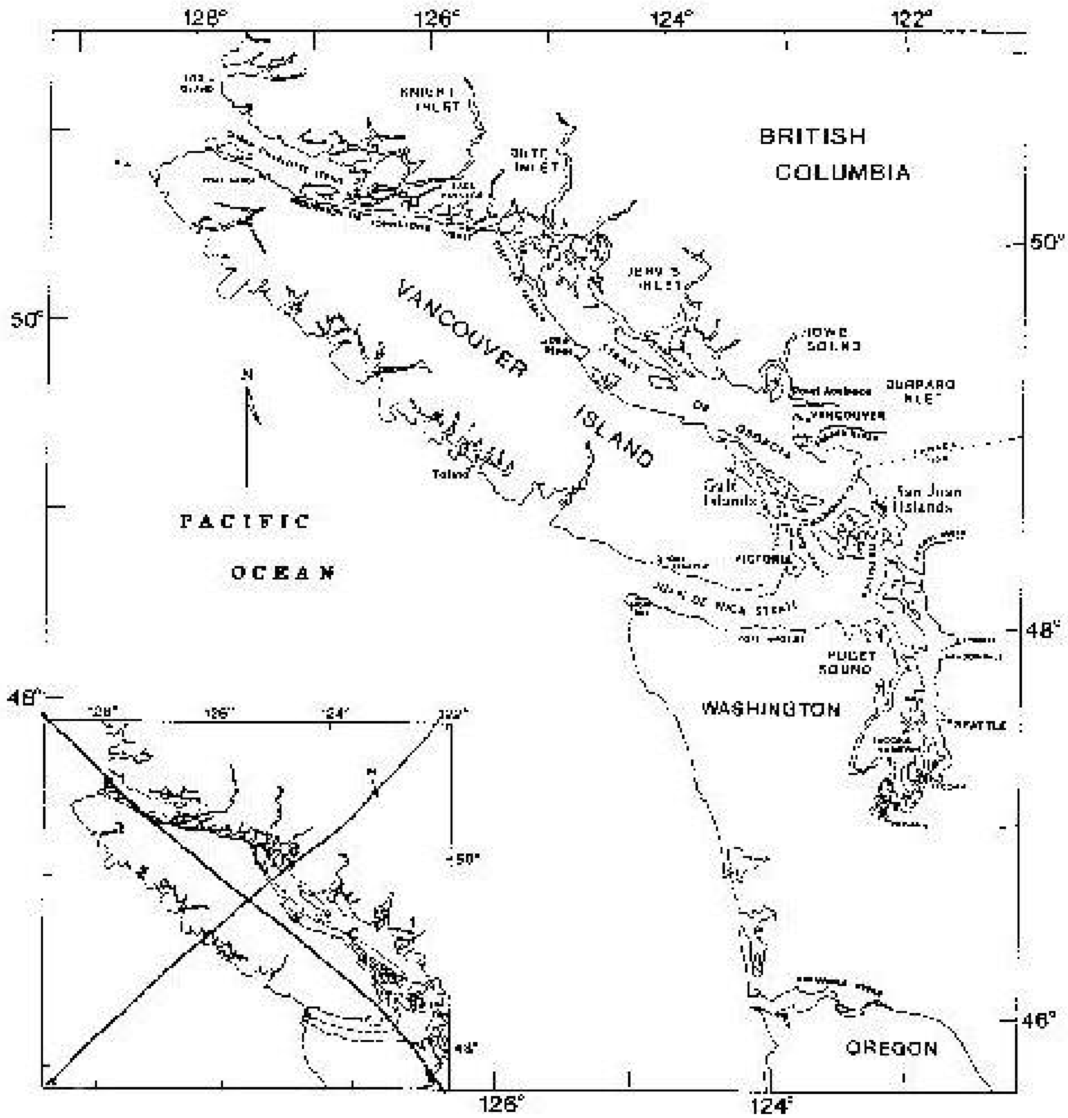

Figure 9

Location map of the study area for British Columbia and Washington waters.

(From Crean et al, 1988)

Figure 10

Location map of the central and northern Strait of Georgia and northern passages (From Crean et al, 1988)

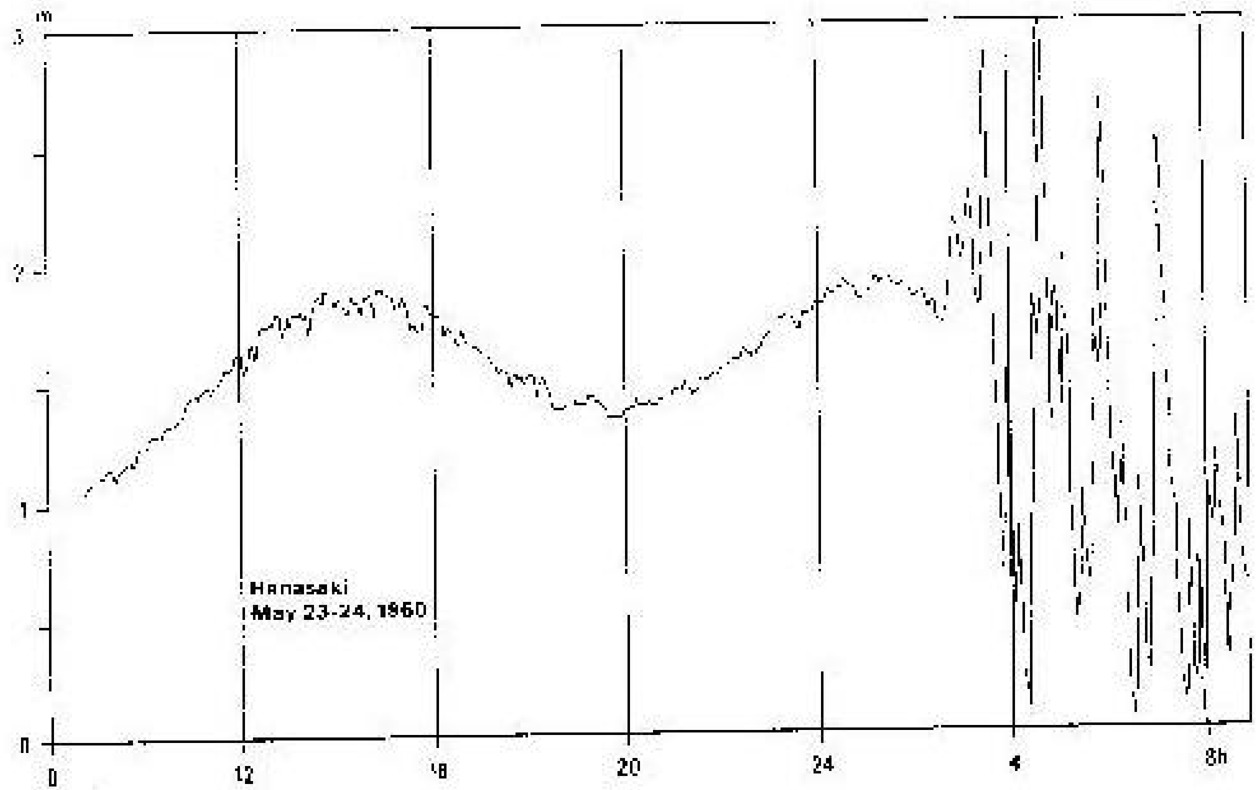

Figure 11

Tsunami forerunner at Hanasaki for the Chilean earthquake tsunami May 1960.
(Nakamura and Watanabe 1961)

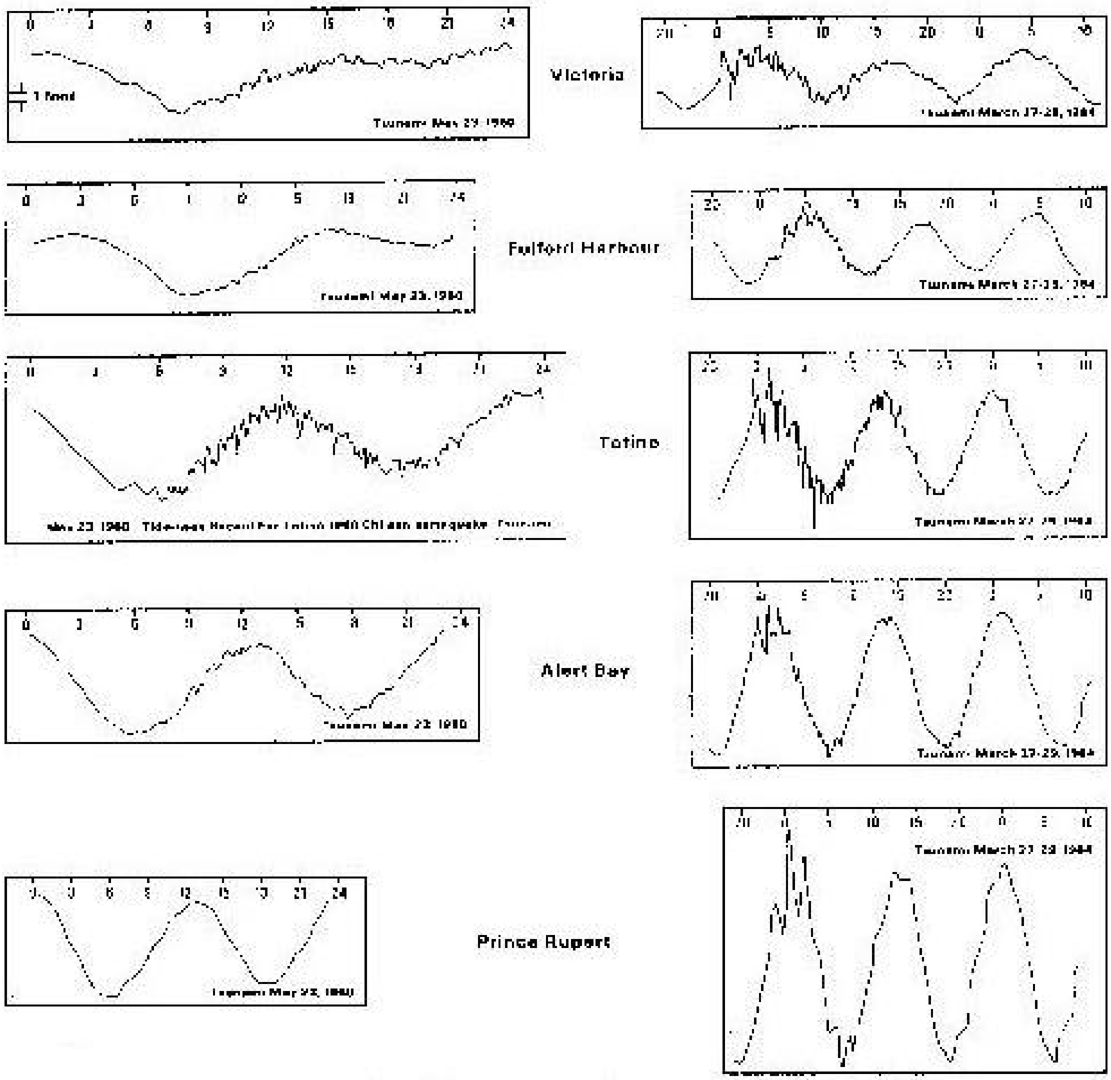

Figure 12

Tidal records for the 1960 Chilean earthquake tsunami and the 1964 Alaskan earthquake tsunami showing no forerunner

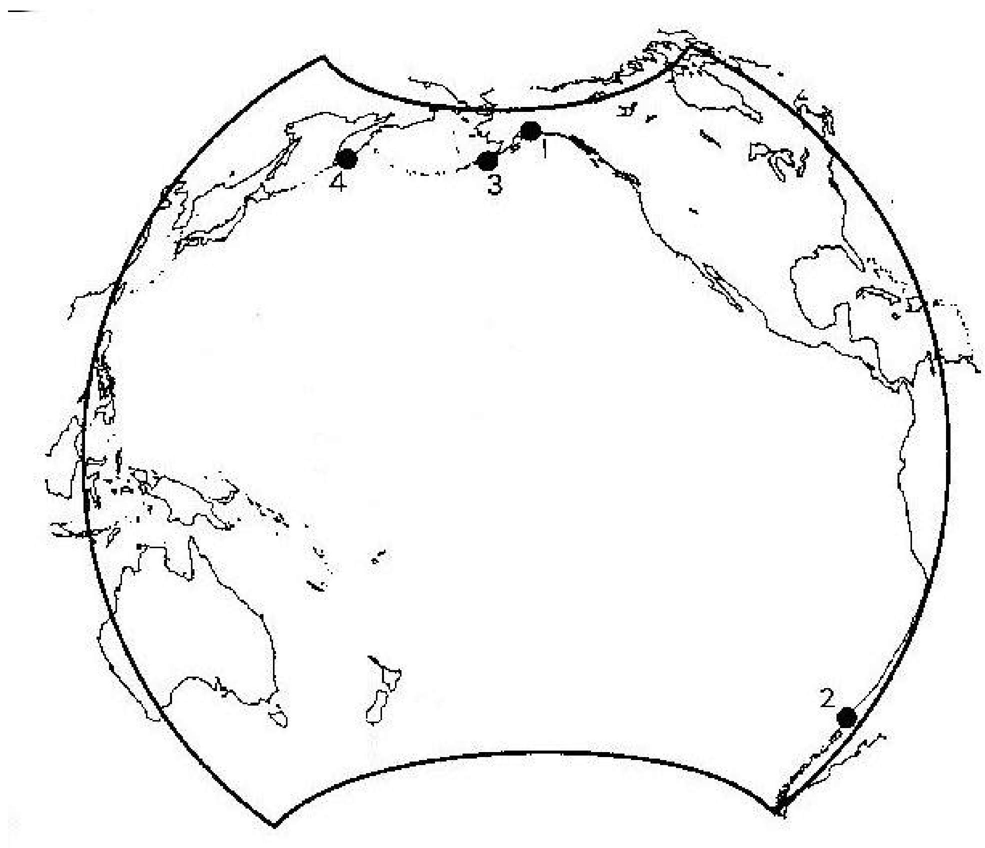

Figure 13

Epicentres of earthquakes used in tsunami simulations. The bold line is the boundary of the deep ocean model (DOM).
(1: Alaska, 2: Chile, 3) Shumagin Gap, 4: Kamchatka)
(From Dunbar et al, 1989a)

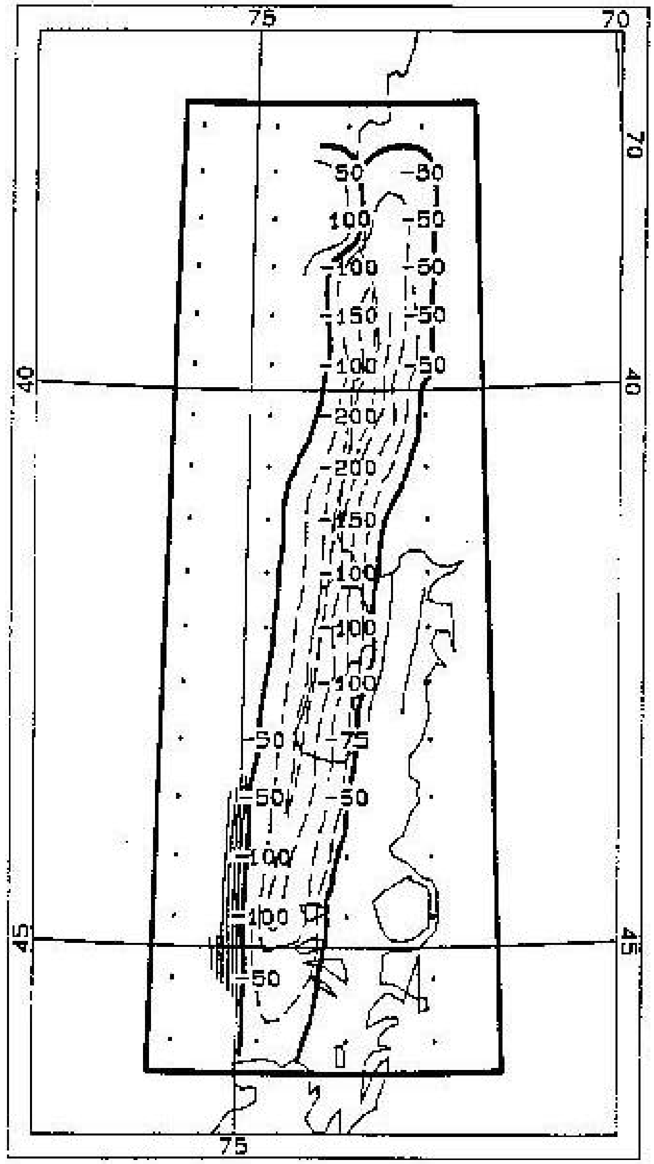

Figure 14

Tsunami generation region for the 1960 Chilean earthquake. Contours and numbers represent final bottom displacements (in cm). Dashed lines indicate downthrust; solid lines represent upthrust; and the bold line corresponds to no vertical movement. Contours were digitized from Plafker and Savage (1970).

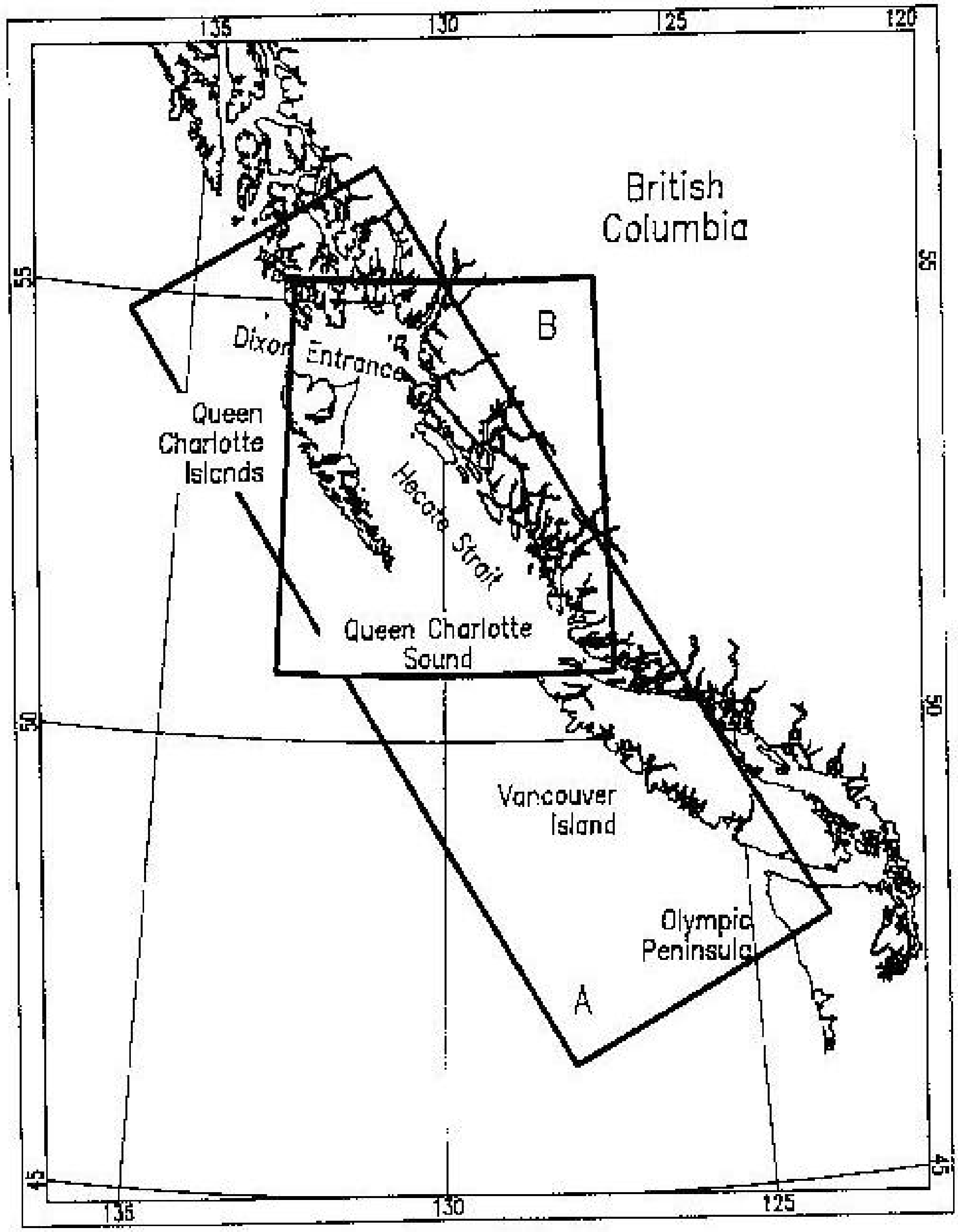

Figure 15

Shelf model grid outline (A) and outline of region used for field plots of northern British Columbia (B).
(From Dunbar et al, 1989a)

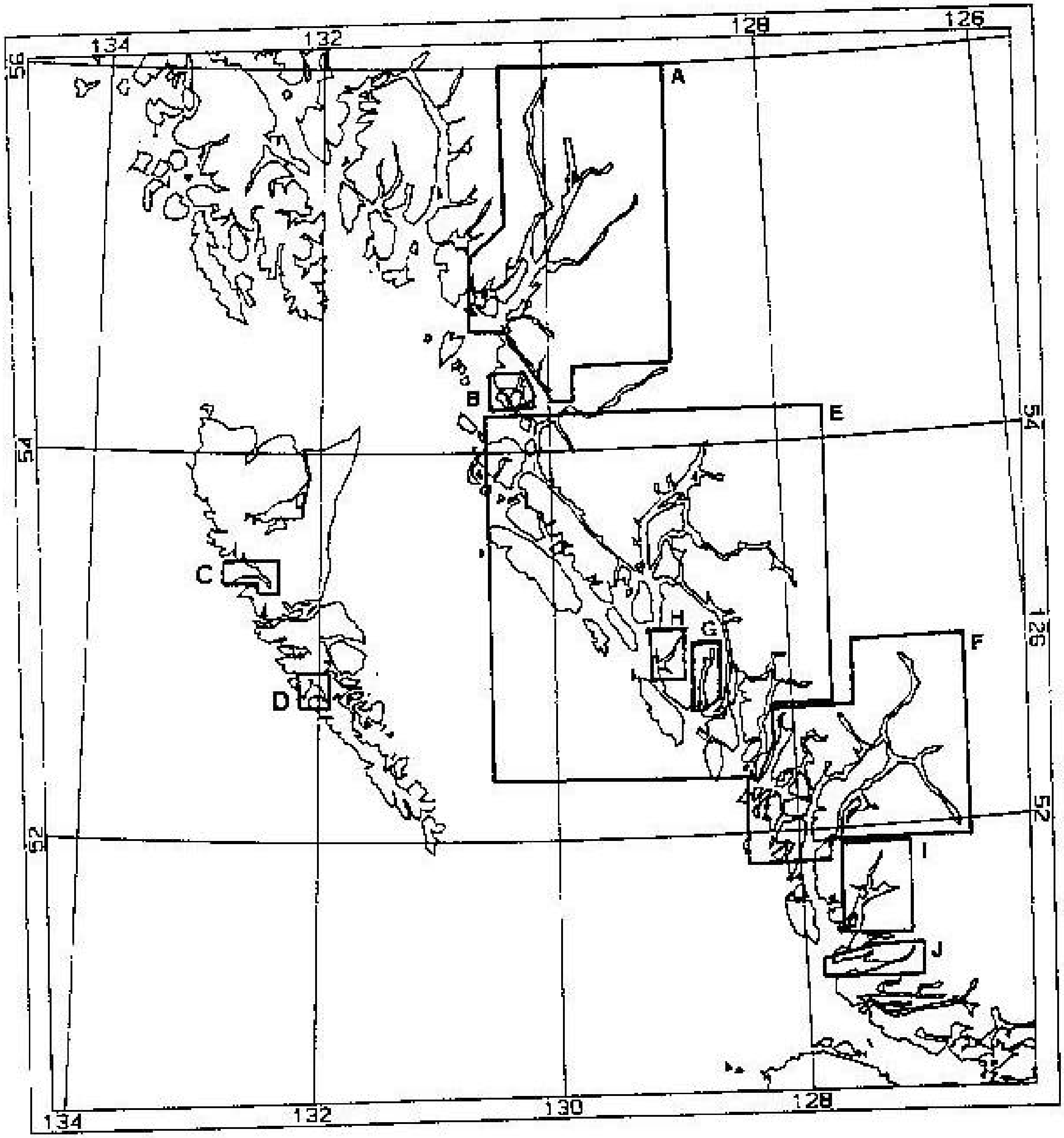

Figure 16

Inlet systems for the north coast of British Columbia
(From Dunbar et al, 1989 a)

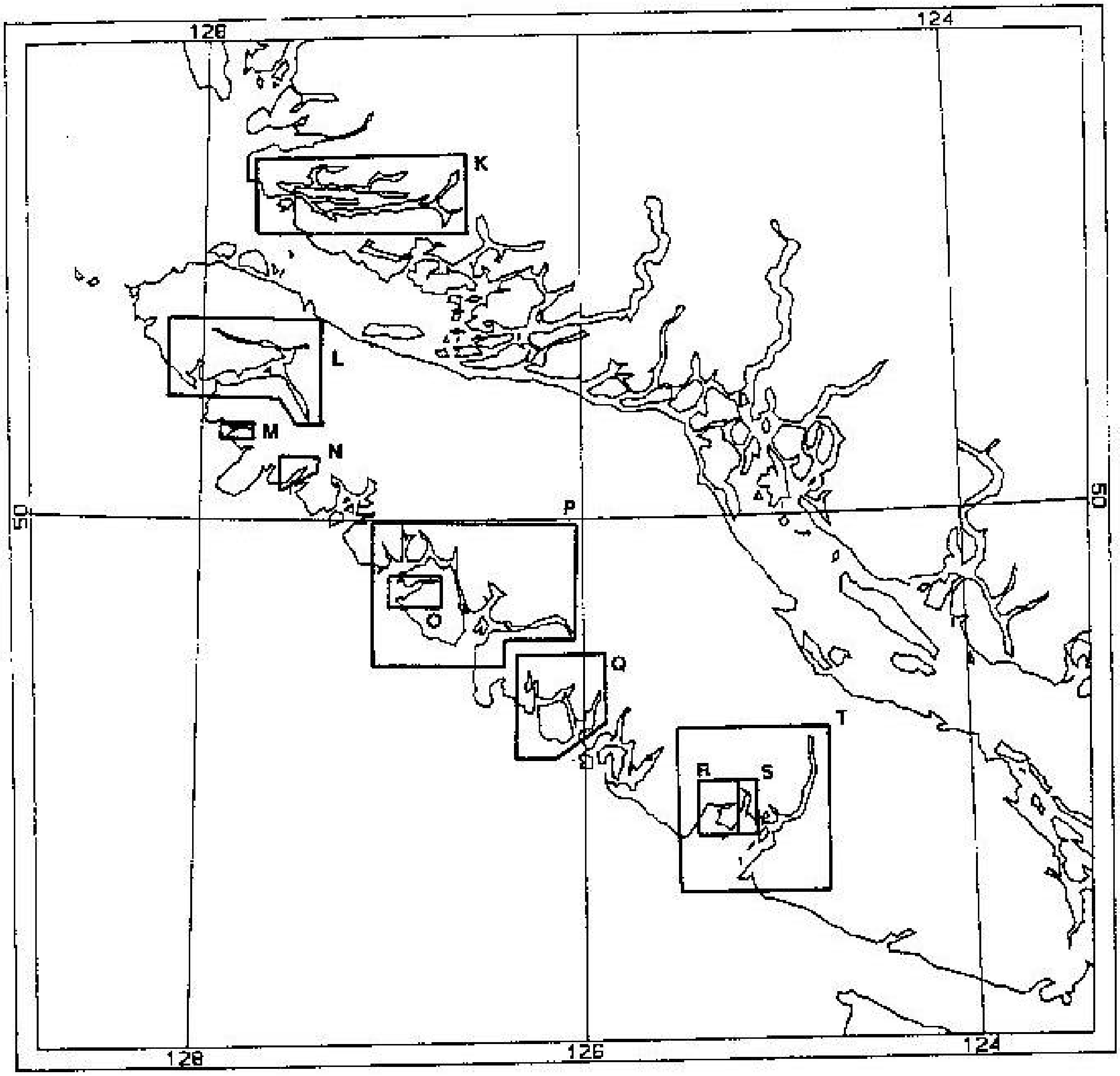

Figure 17

Inlet systems for the south coast of British Columbia
(From Dunbar et al, 1989a)

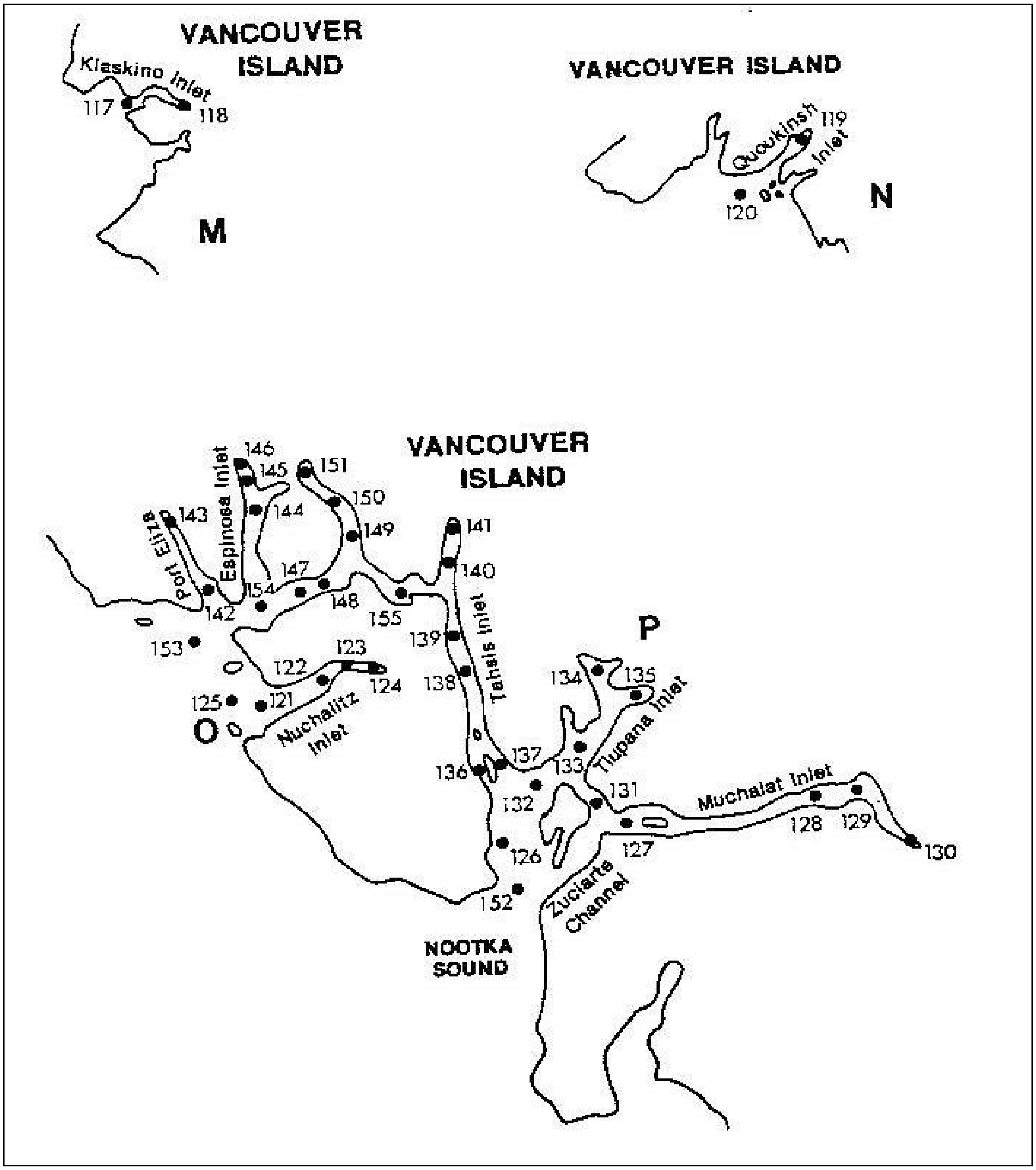

Figure 18

Map showing water level and current locations listed in Table 2
(From Dunbar et al, 1989b)